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# Reducing Siltation and Increasing Hydropower Generation from the Rantambe Reservoir, Sri Lanka

E.P.N. Udayakumara

U.A.D.P. Gunawardena

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**E.P.N. Udayakumara**

Department of Natural Resources
Faculty of Applied Sciences
Sabaragamuwa University of Sri Lanka
Belihuloya, Sri Lanka

**U. A. D. P. Gunawardena**

Department of Forestry and Environmental Science
Faculty of Applied Sciences
University of Sri Jayewardenepura
Nugegoda, Sri Lanka

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A.K. Enamul Haque

**Technical Editor**
Pranab Mukhopadhyay

**Comments should be sent to**

EPN Udayakumara
Email: udayaepn@gmail.com

# Contents

# Abstract

Hydropower in Sri Lanka is affected by unanticipated siltation from changes in upstream watersheds. In this study, we examine the costs of soil erosion associated with the Rantambe reservoir. We assess the impact of changing upstream land use patterns on soil erosion, reservoir sedimentation, electricity availability and dredging costs by using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) Sediment Retention model. We find that the current human-induced average rate of soil erosion in the watershed is 10.7 tons/ha/year, which is approximately double the permissible rate of soil erosion. Consequently, the reservoir bears an annual hydropower loss of some half a million rupees (over three thousand US$) per year. Our model estimates that these hydel losses could be avoided by incurring an annual cost of dredging of Rs. 259,605 (1,782 US$). Three alternative watershed management strategies would also help lower sedimentation. These include: (I) adoption of a Soil and Water Conservation (SWC) by farmers, (II) re-foresting farmlands with slopes greater than 60%, and (III) reforesting 10% of current farmlands. Strategy I would reduce the soil erosion rate relative to business as usual by 23%, strategy II would reduce the rate by 16% and strategy III would lower the soil erosion rate by 11%. Thus, SWC strategy (I) provides the best outcome. Undertaking plot level soil and water conservation (strategy I) would result in electricity revenue savings of 15% (460 US$) per year relative to the current scenario. While we focus on the hydel benefits, it is likely that there are also farm level benefits to soil and water conservation.

**Keywords**

Soil erosion, InVEST model, soil conservation, Sri Lanka, dredging costs, hydropower

*JEL Classification: Q23: Forestry, Q24: Land, Q 25: Water, Q51: Valuation of Environmental Effects*

# Reducing Siltation and Increasing Hydropower Generation from the Rantambe Reservoir, Sri Lanka

## 1. Introduction

Energy production is critical in determining the growth trajectory of any economy. Sri Lanka has no indigenous fossil fuel resources and the only large scale indigenous primary source for conventional generation is hydro resources (Wijayatunga et al., 2006). In 2007, total energy demand in the country was met by a combination of biomass (48%), petroleum (42.5%) and hydropower (9.5%), making the share of renewables about 58%. Hydel is a critical part of this renewable energy that the government is seeking to further expand as part of its strategy to address climate change (Gunawardena, 2010).

While hydroelectricity plays a major role in the power sector in Sri Lanka, the output of hydropower plants can be significantly affected by unanticipated siltation resulting from changes in upstream watersheds. Siltation not only reduces the power generation capacity of hydro-power plants, but also adds to costs of dredging (Gunatilake and Gopalakrishnan, 1999). Thus, even as the country seeks to expand its hydroelectricity, it is important to identify strategies to improve the efficiency of existing power plants. In this context, our study seeks to examine the trade-off between management practices to reduce soil erosion and the increase in energy production in Sri Lanka.

In Sri Lanka, land degradation due to soil erosion is a major concern owing to its adverse consequences on hydroelectricity and agriculture (Udayakumara et al., 2010). According to the Global Assessment of Human Induced Soil Degradation (GLASOD), about 50% of lands in Sri Lanka are degraded (MoENR, 2002). The portions eroded range from less than 10% in some districts to over 50% in other districts. Soil erosion is mainly induced by water flows and soil fertility depletion.

Although the siltation of reservoirs due to soil erosion in upper-catchment areas is widely recognized, there is limited quantitative economic analysis of such effects. This is largely due to the lack of scientific data and various uncertainties attached to understanding reservoir sedimentation (Southgate and Macke, 1989). While there have been a number of international attempts to estimate such costs (Veloz et al., 1985, Southgate and Macke, 1989), few Sri Lankan studies have examined the link between hydroelectricity generation and reservoir siltation. Perhaps the only other study is a nearly twenty-year old effort by Gunatilake and Gopalakrishnan (1999) to examine the impact of sedimentation on lost hydropower production, loss of irrigable area and the additional cost of purifying drinking water in the Mahaweli reservoir.

Our study estimates soil erosion rates in the Uma-Oya watershed that affects the Rantambe reservoir, which has an installed capacity of 52 MW. This reservoir is located in the Central Highlands of Sri Lanka, which generate hydropower that supplies about 5 % of the total power consumption in the country (Hewawasam, 2010).

In order to understand the trade-offs between land use management and hydropower generation, we examine soil erosion and sedimentation rates and calculate avoided dredging costs if land-use patterns change. We estimate, cost of hydropower generation and cost of dredging under the current land use and three other alternative watershed management scenarios. We use the InVEST Sediment Retention model for calculating soil erosion rate in the catchment.

## 2 Data and Methodology

Several soil erosion models have been developed since the 1930s to examine soil erosion rates (Lal, 2001). Methods to assess soil erosion include those based on remote sensing (RS) and geographic information system (GIS), field based methods that monitor soil data and farm level productivity studies and land use modeling. Most of the time, the well-known Universal Soil Loss Equation (USLE) (Wischmeier et al., 1958, Wischmeier and Smith, 1965) and its modifications i.e. Modified USLE and Revised USLE (MUSLE, RUSLE) (Wischmeier and Smith, 1978) are used to estimate soil erosion. The USLE, a simple empirical model based on regression analyses of soil loss rates in the USA, can estimate the long-term annual erosion rates for agricultural fields. Even though this equation has many shortcomings, it is widely used because of its relative simplicity (Desmet and Govers, 1996). In addition, Honda (1993) introduced an empirical equation to estimate soil erosion rates, which is also simple and less data intensive. This has been applied for different sites and satisfactory results have been obtained (Udayakumara et al., 2012) Cosmogenic nuclide-based techniques are also commonly used to quantify natural erosion and other geomorphic processes (Hewawasam et al., 2003).

In terms of the topic of interest, i.e. the impact of erosion on reservoir sedimentation, there are few studies available to assess this in Sri Lanka. According to the few available studies, all eroded materials from the catchments do not move into reservoirs. Only an estimated 20% is delivered to the reservoirs (Wickramasinghe, 1990, Roehl, 1962). Such sediment inflows are assumed to come from the immediate catchment and from outflows of upper reservoirs. Some 75% of the incoming sediments from upper watersheds/reservoirs is expected to be trapped in the reservoirs (Gunatilake and Gopalakrishnan, 1999).

In this study, we applied the InVEST Sediment Retention model in order to map and assess soil erosion and then analyze avoided degrading and hydropower costs etc. due to present land use. InVEST was developed as part of the Natural Capital Project (www.naturalcapitalproject.org), a partnership between Stanford University, the Nature Conservancy (TNC), and the World Wildlife Fund (WWF), working with many other institutions. This model was developed in order to align economic forces with conservation objectives (Nelson et al., 2009).

InVEST combines land use and land management information with information on environmental conditions (e.g., soil and climate information) as inputs into ecological production functions to generate spatially explicit predictions on the supply of ecosystem services. Economic information on the demand for ecosystem services is combined with ecosystem service supply to generate predictions about the use and value of ecosystem services (Bai et al., 2011).

In addition to the InVEST model, to ascertain socioeconomic information in the study area, we surveyed 400 farm households. In addition, a plot level survey (n=400) of all surveyed households was undertaken during the period from March 2014 to August 2014 to obtain information characteristics such as soil depth, color, texture and slope.

### 2.1 Assessing sedimentation in the reservoir with InVEST

The InVEST model uses data from field level (individual parcels) in the watershed to predict the sedimentation rate in the downstream reservoir. It estimates the ability of each parcel to retain sediments based on its characteristics. It then assesses the cost of removing the accumulated sediment in the reservoir on an annual basis. Thus, we use the InVEST model to calculate and map erosion, i.e. the average annual soil loss at the sub-watershed levels and ultimately, the watershed level.

An important determinant of soil retention capacity is land use and land cover (LULC). To identify a land parcel's potential soil loss and ability to sediment transport, the InVEST Sediment Retention model uses the Universal Soil Loss Equation (USLE) at the pixel scale. It integrates information on LULC patterns and soil properties (texture, structure, percent organic matter and permeability), as well as a digital elevation model (DEM), rainfall and climate data to predict changes in erosion.

The pixel-scale calculations allow us to represent the heterogeneity of key driving factors in reservoir water yield such as soil type, precipitation, vegetation type, etc. This model can also be used to value the lands' current activities vis-à-vis alternate strategies that focus on maintaining water quality or avoiding reservoir sedimentation. In the reservoir maintenance case, the model uses additional data on reservoir location and the avoided cost of sediment removal to value a sub-watershed's capacity to keep sediment out of a reservoir.

In addition to base-line analysis, we use the InVEST Sediment Retention model to evaluate three alternative watershed management scenarios. The alternate scenarios are:

**Scenario I:** Application of Soil and Water Conservation (SWC) measures to all vegetable growing plots in the watershed. Currently, some 76 % of farmers practices some SWC measures in some parts of their lands. Commonly practiced SWC measures include: agronomic measures (application of mulch and organic matter), vegetative measures (planting of trees, shrubs and grass and practicing sloping agriculture land technology/SALT), structural measures (constructing terraces, bunds and ditches to reduce erosion) and soil management measures (changing the species composition of crops, controlling cropping intensities and fallow periods).

**Scenario II:** Convert vegetable growing lands that are presently on steep slopes (>60%) to forest. According to the Soil Conservation Act of Sri Lanka, vegetable production on lands above 60% slope is banned. Therefore, this would involve implementing a legal provision. Out of the total land area, 78% is located on slopes more than 30% gradient and 15% of the lands are on more than 60% slope (Bandara and Thiruchelvam, 2010).

**Scenario III:** Increase the existing forest cover area by 10% while decreasing the vegetable growing areas by 10%. According to the LULC map developed by us the current forest cover is currently about 30 %. This scenario proposes to increase forest cover up to 40%.

## 2.2 Study area

Sri Lanka is topographically divided into three major regions viz. Hill Country, Mid Country and Low Country. Our study is based in Uma-Oya watershed (Figure 1) located in Sri Lanka's mid-country. Comparative studies between regions showed that the Mid Country, is the most vulnerable to soil erosion due to number of reasons that include the existence of immature brown soils, marginal tea lands and arable cropping lands with soil erosion induced-crops (MoENR, 2002). This area gets seasonal monsoon rains and the mean annual precipitation varies from 1,000 to 5,000 mm. The watershed drains a mountain range with altitudes between 500 and 2,400 m that is uniformly underlain by crystalline rock. Mean slopes range from 50 to 300. The population in the study area is about 1 million.

The Uma-Oya watershed is one of the most important watersheds in Sri Lanka due to its hydro-electricity contribution. Covering about 765 km2, the watershed consists of Uma Oya (i.e. the major tributary of this watershed) that drains into Rantambe Reservoir. The Rantambe reservoir consists of a 420 m long, 42 m high gravity type concrete dam across the Mahaweli River. It has a power station on the left bank with two turbine-generator units of total installed capacity of 52 MW. The power station is expected to generate 180 Gwh. of firm energy and 73 Gwh. of secondary energy per annum (CEB, 2013).

According to historical records, the Uma-Oya watershed was covered with natural vegetation before large-scale deforestation took place for plantation agriculture in the 19th century (Wickramasinghe, 1988). A major portion of land in the watershed is presently under tea cultivation, which contributes to severe soil erosion (Hewawasam et al., 2003). Population growth in the hill country and expanded settlements and farming in steep slopes have worsened the erosion problem in this area. Because of sedimentation in the drainage systems, flash floods in the lowlands has become a recurrent natural hazard during periods of intense precipitation (Hewawasam, 2010).

## 2.3 Data

The InVEST model examines reservoir sedimentation because of land use change in the watershed. It is a complex system that needs data on multiple attributes of the watershed. We obtained data related to the input variables (Table 1) to build the watershed sedimentation model, as explained below.

Digital elevation model (DEM): DEM, a major input into the InVEST Sediment Retention model, identifies the elevation of different plots in the watershed. The accuracy of DEM is a critical factor for results. Hence, to sustain high accuracy, we created a DEM using Shuttle Radar Topography Mission (SRTM) satellite images with 30m x 30m resolution for the Uma-Oya watershed and its five sub-watersheds (Figure 2).

The rainfall erosivity factor (R): R is a measure of an area's erosion potential that depends on the intensity and duration of rainfall. The greater the intensity and duration of the rain storm, the higher the erosion potential. R is identified through a GIS raster dataset, with a R-factor value for each cell (Figure 3). Uma-Oya watershed has 21 weather stations. We obtained annual rainfall data for the year 2013 from the Department of Meteorology, Sri Lanka. We then generated the R-factor using the Roose equation (Roose, 1996):

$$R = a * procipitation \qquad \textit{Equation 1}$$

Where, a=constant or 0.2, which is standard in tropical mountain areas and precipitation= annual precipitation in millimeters (mm).

Soil erodibility factor (K): Soil erodibility is a measure of the susceptibility of soil particles to detachment and transport by rainfall and runoff (Wischmeier and Smith, 1978). K is a GIS raster dataset, with a soil erodibility value for each cell. Data on erodibility (K) was obtained from the Department of Irrigation, Sri Lanka. K values are based on six major soil types in this watershed and were used generate the soil erodibility map for the watershed (Figure 4).

Land use land cover (LULC): LULC is a measure of the type of land use or land cover in an area. It is generated as a GIS raster dataset with an integer LULC code for each cell. In order to generate a LULC map of the study area, LANDSAT satellite images with 30m x 30m resolution were used. Eight LULC classes were made (Figure 5) based on the ERDAS (Earth Resources Data Analysis System) image processing environment.

Watershed and sub-watersheds: Watersheds and sub-watersheds are identified as GIS maps. A watershed is a shape file of polygons. This is a GIS layer of watersheds such that each watershed contributes to a point of interest where water quality will be analyzed. Sub-watersheds are also a shape file of polygons and identified as a GIS layer of sub-watersheds, contained within the watersheds, which contribute to the points of interest where water quality will be analyzed. We first used the Watershed Tool in the ArcGIS software to delineate the watershed (Figure 6). Then, sub-watersheds were demarcated separately. Finally, the demarcated sub-watersheds were merged together (Figure 7).

Biophysical table: We include in our model information on each land use (LULC) class related to crop (C-factor), management factor (P-factor) and sediment retention value (Table 2). The C-factor of land depends on crop type and the tillage method used. For this study, C-factor values were obtained from a case study of Santubong River (Kuok et al., 2013). The land use type and respective C-factor values are given in Table 3. P-factor depends on the support practice methods (Stone and Hilborn, 2000). Earlier work has used one P-factor value for each LULC type (Kuok et al., 2013). Therefore, we too followed the same procedure assuming that support practice factor is the same in identical LULC plots (Table 4). We obtained data on P-factors from (Kuok et al., 2013). The sediment retention value is a percentage value which reflects the capability of the land use type to retain sediment coming from upper lands (Stone and Hilborn, 2000). Considering each land use type, subjective sediment retention values were given (Table 5).

Threshold flow: This is defined as the number of upstream cells that must flow into a downstream cell before it is considered part of a stream. The model's default value 1,000 was accepted for this study.

Slope threshold: This is an integer slope value, which is dependent on landscape characteristics such as slope management practices including terracing and slope stabilization techniques. It depends on the DEM resolution and the terracing practices used in the region. Up to a certain slope, farmers tend to cultivate without any soil and water conservation measure (terracing or any slope stabilization systems). The slope value at which they start taking protective measures is considered as the slope threshold. Using the observations during our field excursions, the average slope threshold value was identified as 75%.

Sediment valuation: An important aspect of the modeling exercise is identifying the cost of sediment dredging and the cost of purifying water. The main use of the reservoir in the study area is for hydropower and irrigation. Because the reservoir is in a remote area, water supply to households for dinking is limited. Therefore, we do not consider water purification costs. Hence, we focus on identifying the benefits from increased hydropower supply and reduced dredging as a result of reduced sedimentation. Information obtained through personal communications with engineers at the Ceylon Electricity Board (CEB) indicates that the cost of sediment dredging in our study reservoir is 2 US$/m3.

Sediment threshold: This is annual the sediment load threshold, which is based on the remaining designed lifetime (26 years) of the reservoir, dead volume (1,400,000 m3) and permissible annual sediment loading (470 metric tons) to the reservoir. This information was also obtained from personal communications with Ceylon Electricity Board (CEB).

# 3 Results and Discussions

Our household survey revealed that the average household size in the area is 4 and the average age of the household head is about 51 years. Seventy-six percent of the farmers of the study area practice some SWC conservation measures such as mulching, terraces, ditches, shade trees and grasses. The market garden is a prominent land use in the watershed (38%), where vegetables such as tomato, beetroot, carrot, bean, knol-khol, leeks, curry-chilli, chilli, potato etc. are grown in small plots for commercial purposes. Other land uses include forests (33%), tea (24%) and others (5%) (Figure 5).

## 3.1 Soil erosion assessment

According to the produced Digital Elevation Map (Figure 2), the study area's elevation ranges from 158m to 2,510m. The calculated rainfall erosivity (R) of the watershed ranges from 692.7 to 1,149.8 (Figure 3) and soil erodibility (K) varies from 0.22 to 0.27 (Figure 4). The watershed can be categorized into eight major land use cover (LULC) classes (Figure 5). The delineated watershed has as area of 760 km2 and includes five main sub watersheds (Figure 7). The biophysical table (Table 2) describes sediment retention in the watershed due to existing cropping type and conservation measures.

Figure 8 shows that the average rate of soil erosion in the watershed is 10.7 t/ha/yr. Compared to the adjacent 'Samanalawewa catchment', Uma-Oya watershed's average annual soil erosion rate is about two times higher[1]. The current rate of erosion is also two times higher than the permissible soil rate of 5t/ha/yr of the region (Jha et al., 2009).

The soil erosion rate in the Uma-Oya watershed varies widely from 0 to1,493.1 t/ha/yr, reflecting different land use practices in the area (Figure 8). In addition to watershed level soil erosion, we were able to calculate sub-watershed level soil erosion rates. These range from 18.6 to158.1 t/ha/yr (Figure 9) The soil loss at sub-watershed levels is shown in Figure 9 and Figure 10. Figure 9 indicates high soil erosion rates in Sub-watersheds 4 and 5. This is possibly due to higher cultivation of vegetables such as potato, tomato, leaks, beetroot etc. in this sub-watershed. While sub-watershed 3 shows moderately high rates, sub-watersheds 1 and 2 have relatively low soil erosion rates. The land cover in sub-watersheds 1 and 2 is different from the other sub-watersheds as this area is forested and has a protected area.

We examine three alternative management strategies to reduce the existing soil erosion rate. In the first scenario, we assume that all the famers adopt SWC measure for their vegetable lands. Currently 76% of farmers undertake SWC measures. Thus, under this scenario we assume that this percentage increases from approximately 75% to 100% SWC adoption in all vegetable growing plots. We then model and map soil erosion in the watershed. As a

[1] The average soil erosion rate in the Samanalawewa catchment: 4.3 t/ha/yr Udayakumara, E. P. N., Shrestha, R. P., Samarakoon, L. & Schmidt-Vogt, D. 2010. People's perception and socioeconomic determinants of soil erosion: A case study of Samanalawewa watershed, Sri Lanka. International Journal of Sediment Research, 25, 323-339..

result of this strategy the average soil erosion rate decreases from 10.7 t/ha/yr to 8.2 t/ha/yr, i.e. a decrease of 23% relative to business as usual. With SWC measures, 85% of the watershed would be within the permissible soil erosion rate category of land (Figure 11).

In the second scenario, the strategy is to comply with the Soil Conservation Act (PoDSRSL, 1996 ) of Sri Lanka, which mentions that cultivation on steep slopes is not permitted. This scenario asks what would happen to soil rate loss if all the steep slope cultivated lands, i.e. slopes with greater than 60% gradient, are converted to forest lands. We find that the average soil loss is 9.0 t /ha/yr or a decline in the erosion rate of 16 % relative to business as usual. This strategy would result in 74 % of the lands falling in the permissible soil erosion category (Figure 12).

Finally, in the third scenario, we examine the impact of an increase in forest cover by 10%, which translates to a corresponding reduction in existing crop lands by 10%. This would limit soil erosion rate to 9.5 t/ha/yr or an 11 % improvement over the current average rate of erosion (Figure 13). This would result in nearly 73 % of the land falling within the permissible soil erosion category.

## 3.2 Cost analysis

The cost analysis considers the loss in hydropower generation and the additional costs of dredging for the remaining lifetime of the project i.e. up to 2040. First, based on the existing soil erosion rate of the catchment, sediment delivery ratio and reservoir trapping efficiency, sedimentation of the reservoir was calculated. This is compared to the sedimentation in the reservoir and consequent loss in electricity if three different alternative catchment management strategies are adopted.

Table 6 shows the sediment retention under business as usual conditions and in the three alternate scenarios. As discussed earlier, the sediment delivery ratio and the sediment trapping efficiency of the catchment are 20% and 75% respectively (Gunatilake and Gopalakrishnan, 1999, Wickramasinghe, 1990, Roehl, 1962). Hence, while all the eroded materials that comes to the catchment does not reach and accumulate in the reservoir, what is retained affects hydropower generation capacity. The existing land use has the highest sedimentation rate (194,704 t/yr) relative to alternate management scenarios. Scenario I (SWC) shows the least sedimentation of the reservoir i.e. 166,017 t/yr, followed by Scenario II (around 175,197 t/yr), and Scenario III (180,934 t/yr ).

In Table 7, we calculate the loss of reservoir capacity under business as usual and the three alternate scenarios. Assuming a bulk density of sediment of 1.5 t/m3 (noting that Bulk density=Mass/Volume) and based on the sediment volumes in Table 6, we first project the amount of area of the reservoir that gets filled as a result of soil erosion. According to the literature, to generate 1 gigawatt hour (GWhr) of electricity, about 0.156 water million cubic meters (MCM) is needed (Gunatilake and Gopalakrishnan, 1999). We then estimate the decline in hydroelectricity generation per annum as a result of the reservoir area being filled. We estimate that in the business as usual scenario, the capacity or area of water loss is 0.12980 MCM/yr per year. Thus, the current hydel losses from sedimentation are 0.020 GWh/yr. Alternate land use practices would reduce the annual electricity losses relative to this baseline by 15% (Scenario I), 10 % (Scenario II) and 7 % (Scenario III) as shown in Table 7.

In Table 8, we estimate the value of losses and the costs of dredging. Based on the electricity average price of Rs. 22.50/KWhr, we calculate that the additional revenues that would be obtained in the absence of sedimentation in Scenario I is Rs. 67,050 (460 US$), in Scenario II is Rs. 45,450 (312 US$) and Scenario III is Rs. 31,950 (219 US$) per year, relative to the business as usual case.

In order to continuously retain reservoir capacity, the reservoir needs to be dredged and this adds to the costs of reservoir maintenance. We were able to calculate the dredging cost in the business as usual case based on reservoir sedimentation by assuming a dredging cost to be 2 US$/yr (Table 8). This amounts to Rs. 259,605 (1,782 US$) per year.

We estimate the present values of loss electricity and dredging using a ten percent discount rate[2]. This reservoir was built in 1990 and the lifetime is assumed as 50 years. According to the current business as usual situation, present values of lost hydropower is Rs. 4 million (0.3 US$ million). Thus, as a result of soil erosion, the authorities are losing over four million rupees in electricity revenues. The cost of dredging to avoid these losses is Rs. 2.4 million (0.02 US$ million). Adoption of SWC measure would result in lowering the loss of hydroelectricity and dredging costs (Table 8).

## 4 Conclusions and Policy Recommendations

Our study estimates that the average annual soil erosion rate in the Uma-Oya watershed due to current land use is 10.7 t/ha/yr. However, this rate varies significantly from 0 to 1,493 t/ha/yr based on different land uses in the watershed. When the values are compared with nearby catchments, the Uma-Oya soil erosion rate is about two times higher. In the study area, sub-watersheds that are forested or have protected areas have a very low soil erosion rates. The highest rates of erosion are in sub-watersheds that are predominantly used for crops.

Because of existing land use, some 194,704 tons of sediment are deposited in the Ranatambe reservoir every year, contributing to some 0.0203 GWhrs of electricity losses per year. This results in a loss of nearly half a million rupees (Rs. 0.455 million or 3,123 US$) per year in revenues to the electricity provider. Over the remaining life of the project these losses in present value terms amount to some four million rupees. This loss could be avoided by dredging the sediments at an annual dredging costs of 0.260 million (1,784 US$).

We suggest three alternate management strategies in order to lower the existing soil erosion and reduce electricity losses from the Rantambe reservoir. Adoption of soil and water conservation measures will reduce the average soil erosion rate in the watershed by 23%, converting all lands in steep areas with gradient more than 60% to forests will result in a 16% decline in the soil erosion rate and converting 10% of agricultural lands to forests will contribute to a 11% reduction in the average soil erosion rate.

Of three strategies, adoption of soil and water conservation measures at the farm level contributes the highest economic gains. Undertaking plot level soil and water conservation (strategy I) would result in electricity savings of 15% relative to the current scenario or Rs. 67,050 (460 US$) per year. Some farm field characteristics such as the Rainfall erosivity factor (R) and soil erodibility (K) factor cannot be altered as they are inherent qualities of rainfall and soils of the farmland. However, length and slope, type of crops and use of soil and water conservation measures can be changed. For instance, terraces may be constructed to reduce the slope length and new crop types and tillage methods can be adopted to reduce erosion.

While our analyses points to the need to change farm level land use and land cover to maximize the returns to hydel plants, we have not estimated the costs or benefits to farmers of changing their farm level practices. We have not explored the costs of adopting any of the three proposed scenarios. This is an aspect that needs to be studied to get a more complete understanding of alternatives. However, our analyses suggest that if some of the benefits to the hydropower plant from changing land use practices are used to create incentives to the farmers to change the land, this may result in a win-win situation.

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[2] This is the current interest rate used by the Sri Lanka's Central Bank

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## Tables

### Table 1: Data used for the InVEST Sediment Retention model and sources

| No. | Data used | Sources |
|---|---|---|
| 1 | Digital elevation model (DEM) | SRTM satellite images (2014) |
| 2 | Rainfall Erosivity Factor | Roose equation was used with rainfall data from 21 rainfall gauging stations in study area from the year (2014) |
| 3 | Erodibility | Existing values from the Department of Irrigation (Hasselo and Sikurajapathy, 1985) |
| 4 | Land Use and Land Cover Type (LULC) | Supervised Classification using LANDSAT Satellite Image (2014) |
| 5 | *Watershed* | Demarcation based on the Watershed tool in the ArcGIS™ 10 |
| 6 | *Sub-watershed* | -do- |
| 7 | *Bio-physical table* | From existing (C and P factors) |
| 8 | *Sediment Threshold* | Mahaweli Authority of Sri Lanka |
| 9 | *Threshold Flow Accumulation* | From available global data (Tallis et al., 2013) |
| 10 | *Slope Threshold* | Field survey of 400 plots in the watershed |

### Table 2: Biophysical Table

| Object ID | lucode | LULC_desc | usle_c | usle_p | Sedret_eff |
|---|---|---|---|---|---|
| 1 | 3 | Water | 1 | 1 | 5 |
| 2 | 4 | Dense forest | 3 | 200 | 100 |
| 3 | 5 | Forest | 3 | 200 | 80 |
| 4 | 7 | Rock | 1 | 1 | 5 |
| 5 | 8 | Tea | 200 | 400 | 40 |
| 6 | 9 | Paddy | 10 | 200 | 40 |
| 7 | 10 | Bare land | 10 | 200 | 5 |
| 8 | 13 | Crop | 500 | 400 | 25 |

NB. lucode =Land use code, LULC_desc = Descriptive name of land use land cover class, USLE_C= Cover-management factor for the usle, USLE_P= Support practice factor for the usle, sedret_eff=The sediment retention value for each LULC class

### Table 3: C-factor value for each land use type

| Land use type | C-factor |
|---|---:|
| Water Features | 0.001 |
| Tropical Upper Montane Forest | 0.001 |
| Tropical Sub-Montane Forest | 0.003 |
| Rocks | 0.001 |
| Paddy | 0.2 |
| Tea | 0.2 |
| Grass Land | 0.01 |
| Crop | 0.1 |

Source: On-site effects of cassava cultivation and soil erosion on the environment, (1999) and Evaluation of C and P Factors in Universal Soil Loss Equation on Trapping Sediment: Case Study of Santubong River,(*Kuok et al*., 2013).

### Table 4: P-factor value for each land use type

| Land use type | P-factor |
|---|---|
| Water Features | 0.001 |
| Tropical Upper Montane Forest | 0.1 |
| Tropical Sub-Montane Forest | 0.1 |
| Rocks | 0.001 |
| Paddy | 0.15 |
| Tea | 0.5 |
| Grass Land | 0.2 |
| Crop | 0.25 |

Source: Universal Soil Loss Equation,(*Stone and Hilborn*, 2000) and Evaluation of C and P Factors in Universal Soil Loss Equation on Trapping Sediment: Case Study of Santubong River, (*Kuok et al*., 2013)

### Table 5: Sediment retention value for each land use type

| Land use type | Sediment Retention Values (%) |
|---|---|
| Water Features | 80 |
| Tropical Upper Montane Forest | 100 |
| Tropical Sub-Montane Forest | 100 |
| Rocks | 1 |
| Paddy | 80 |
| Tea | 90 |
| Grass Land | 75 |
| Crop | 25 |

### Table 6: Soil erosion under alternative management systems

| Management system | Total erosion at catchment (t/yr) | Sediment inflow from the catchment (t/yr)[a] | Sediment inflow from the outflow of the upper reservoirs (t/yr)[b] | Total sediment inflow (t/yr) | Sediment outflow (t/yr)[c] | Sediment deposition (t/yr) (Figure 14) |
|---|---|---|---|---|---|---|
| Existing land use | 818550 | 163710 | 95896 | 259606 | 64901 | 194704 |
| Scenario I | 627300 | 125460 | 95896 | 221356 | 55339 | 166017 |
| Scenario II | 688500 | 137700 | 95896 | 233596 | 58399 | 175197 |
| Scenario III | 726750 | 145350 | 95896 | 241246 | 60311 | 180934 |

NB. Scenario I (adoption of SWC measures in all farmlands), II (steep slope farmlands (>60%) converted to forests) and III (10% of existing farmlands converted to forests)

[a] Assuming 20% deposit from land erosion

[b] Assuming 100% deposit from upper reservoir (as Ranatambe reservoir is situated just below the Randenigala reservoir in a chain of hydel reservoirs)

[c] Assuming 25% sediment outflow from the inflow sediment from the Rantambe reservoir

### Table 7: Loss of hydropower generation capacity under alternative management systems

| Management system | Loss of reservoir capacity or area loss[d] (MCM/yr)[f] | Electricity generation (GWh/MCM) | Annual loss in electricity generation[e] (GWh/yr)[h] |
|---|---|---|---|
| Existing land use | 0.12980 | 0.156 | 0.02024 |
| Scenario I | 0.11068 | 0.156 | 0.01726 |
| Scenario II | 0.11680 | 0.156 | 0.01822 |
| Scenario III | 0.12062 | 0.156 | 0.01882 |

NB. Scenario I (adoption of SWC measures in all farmlands), II (steep slope farmlands (>60%) converted to forests) and III (10% of existing farmlands converted to forests)

[d] Loss of reservoir capacity or area loss (MCM/yr)=Sediment deposition (t/yr)/Bulk density of sediment (t/m$^3$)

[e] Annual loss in electricity generation (GWh/yr) = Loss of reservoir capacity or area loss (MCM/yr) x Electricity generation (GWh/MCM)

[f] MCM/yr = Million cubic meters, hGWh/yr = Gigawatt hours

### Table 8: Annual and present values of loss in electricity and dredging

| Management system | Annual value of loss electricity (Rs/yr) | Present value of loss electricity (Rs) | Annual value of cost of dredging (Rs/yr) | Present value Cost of dredging (Rs) |
|---|---|---|---|---|
| Existing land use | 455400 | 4133684 | 259605 | 2356448 |
| Scenario I | 388350 | 3525068 | 221356 | 2009257 |
| Scenario II | 409950 | 3721133 | 233596 | 2120360 |
| Scenario III | 423450 | 3843673 | 241245 | 2189794 |

NB. Scenario I (adoption of SWC measures in all farmlands), II (steep slope farmlands (>60% ) converted to forests) & III (10% existing of farmlands converted to forests). The reservoir was built in 1990 and the lifetime is assumed as 50 years. For remaining life time (25 years), PV was estimated 10% discount rate is assumed.

## Figures

**Figure 1: Uma Oya watershed**

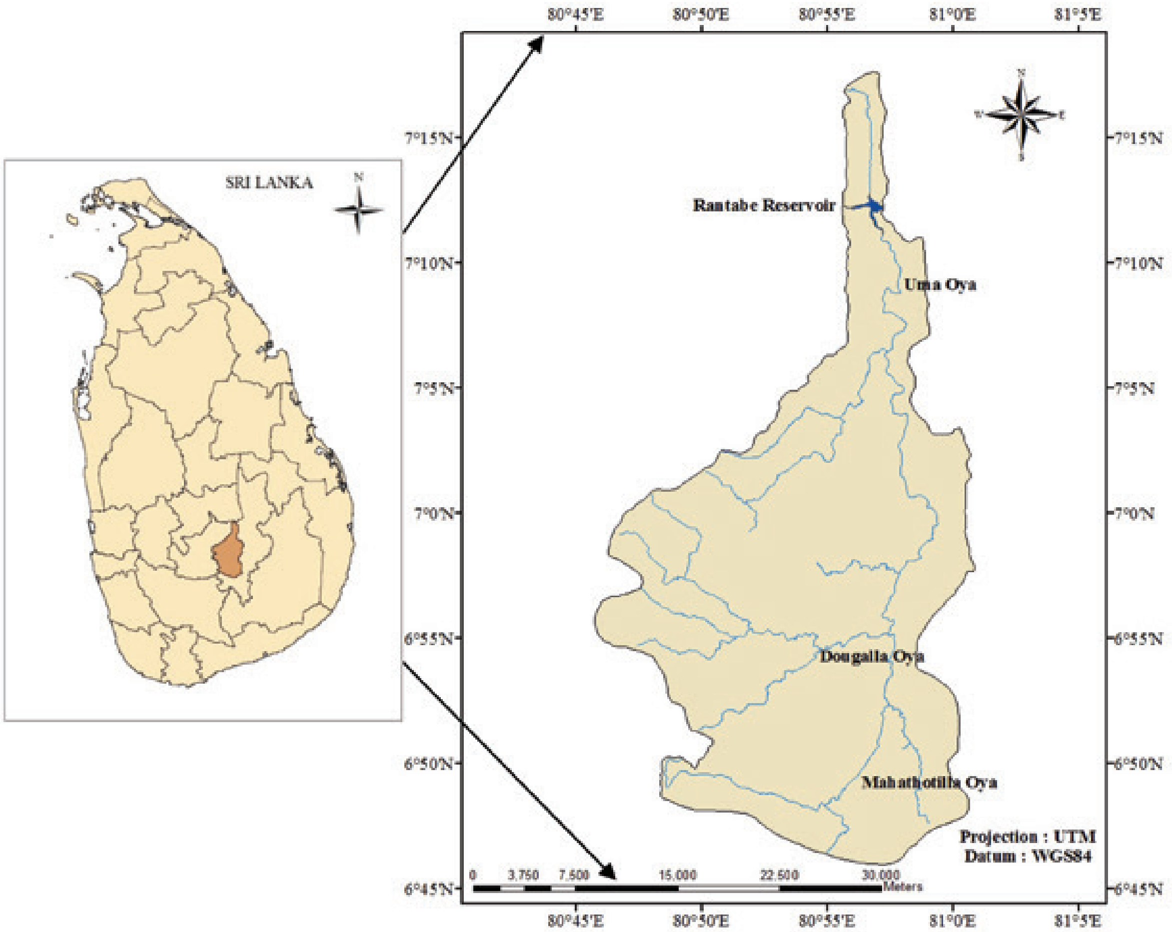


**Figure 2: Digital elevation model (DEM)**

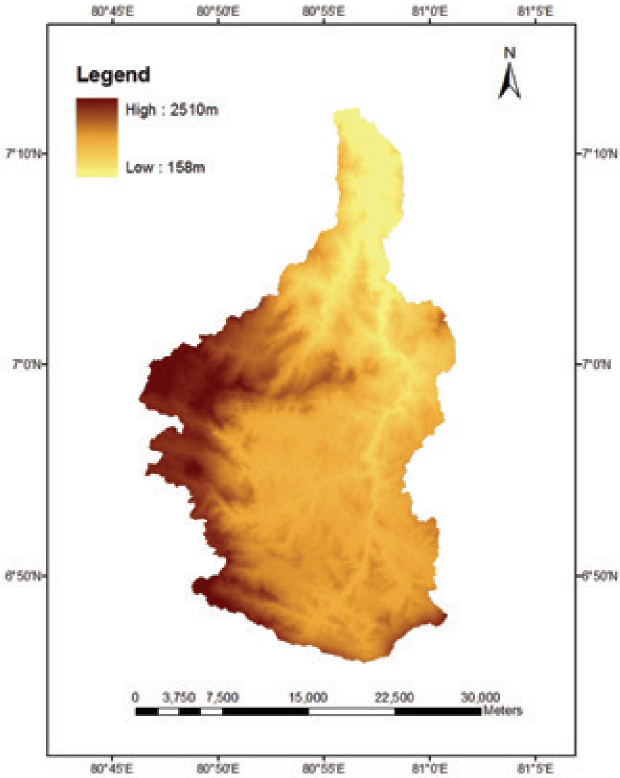



**Figure 3: Soil erosivity map**

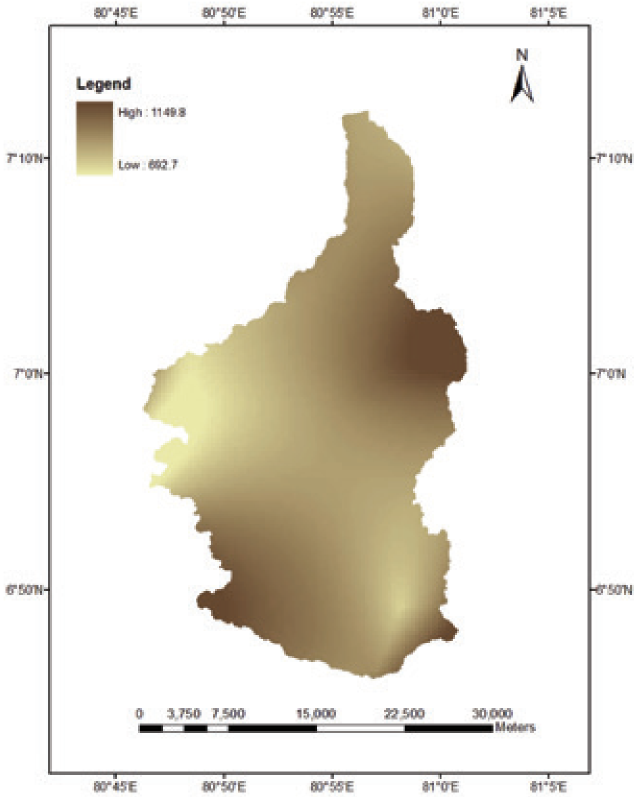


**Figure 4: Soil erodibility map**

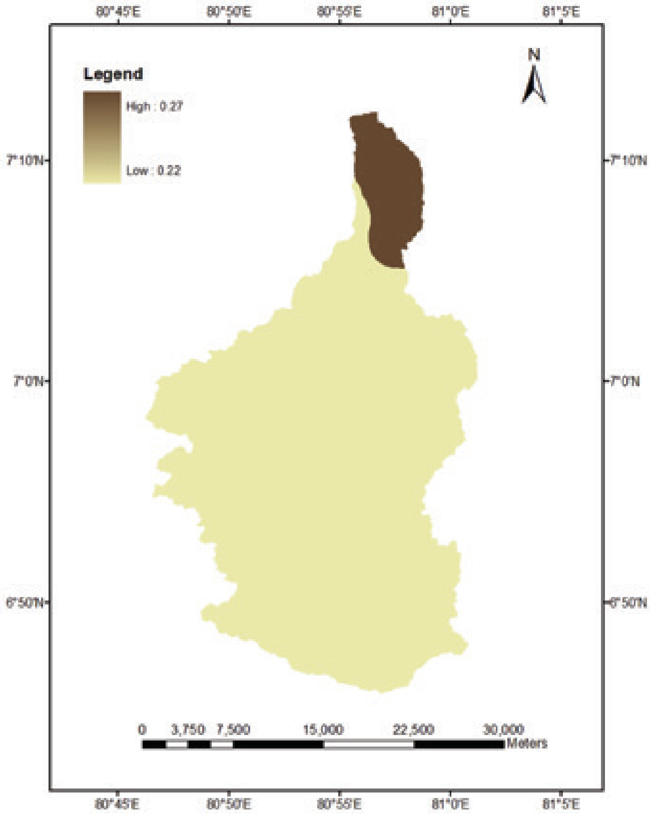



**Figure 5: Land use land cover map**

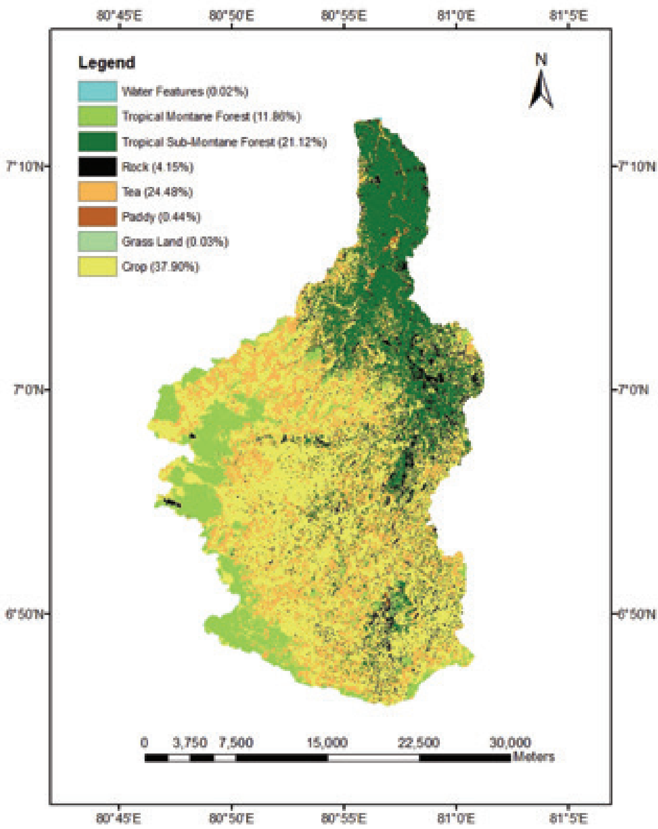


**Figure 6: Delineated watershed area**

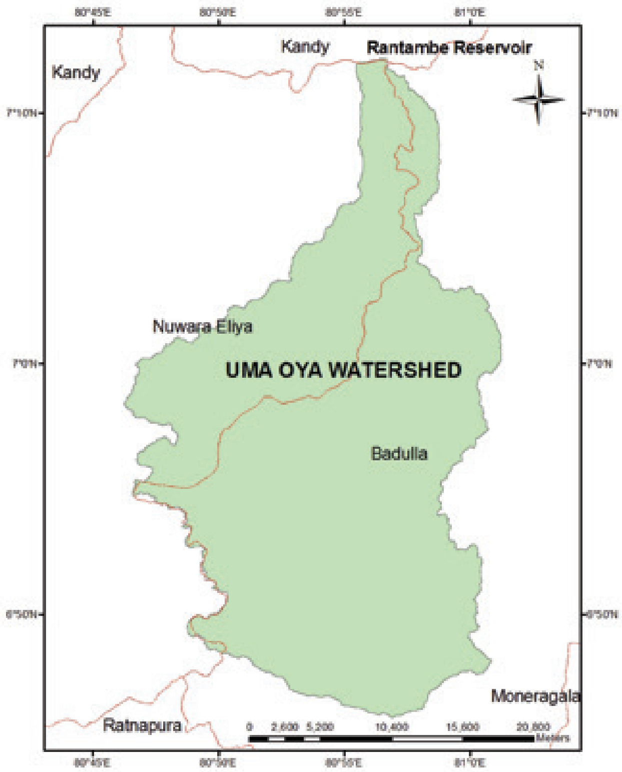



**Figure 7: Delineated sub watershed areas**

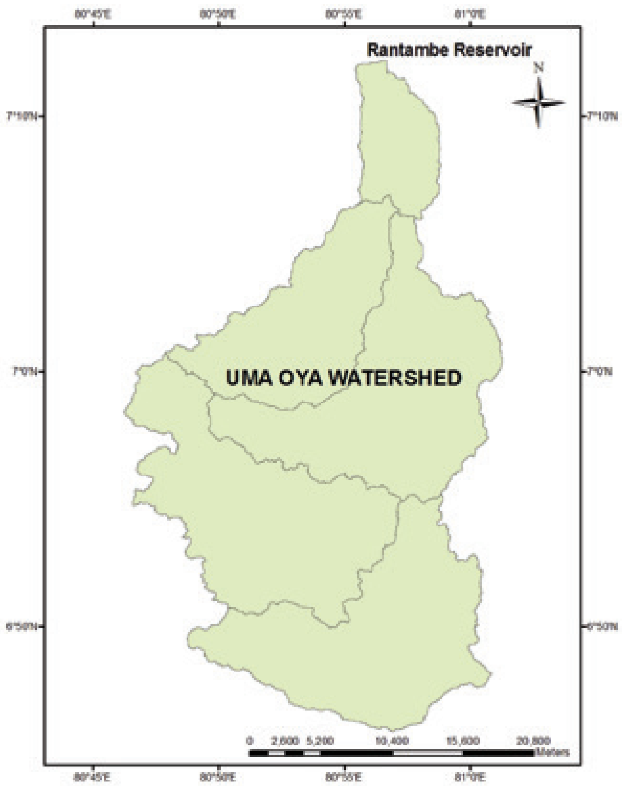


**Figure 8: Pixel based soil erosion**

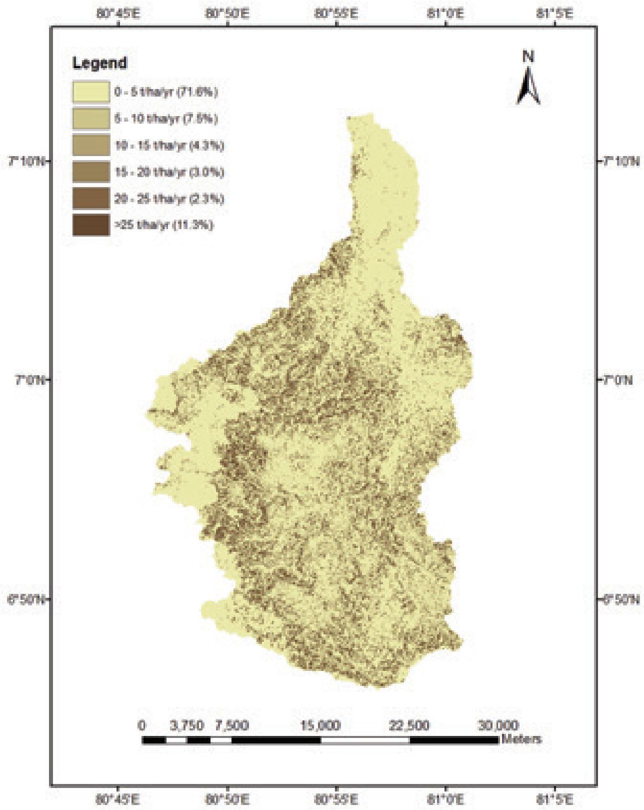



Figure 8: Pixel based soil erosion

**Figure 9: Sub-watershed based soil erosion (t/ha/yr)**

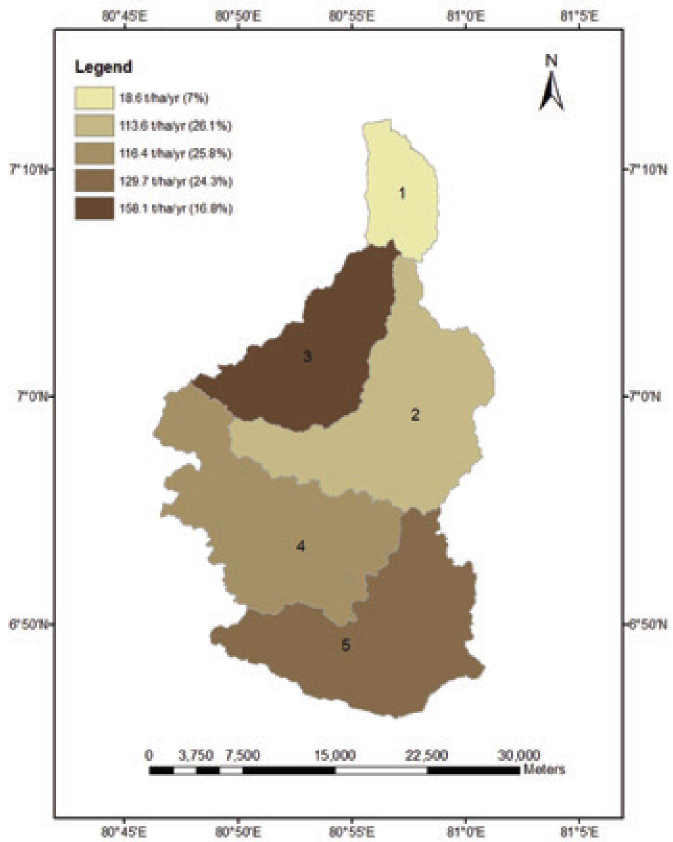


**Figure 10: Sub-watershed base soil erosion (t/sw/yr)**

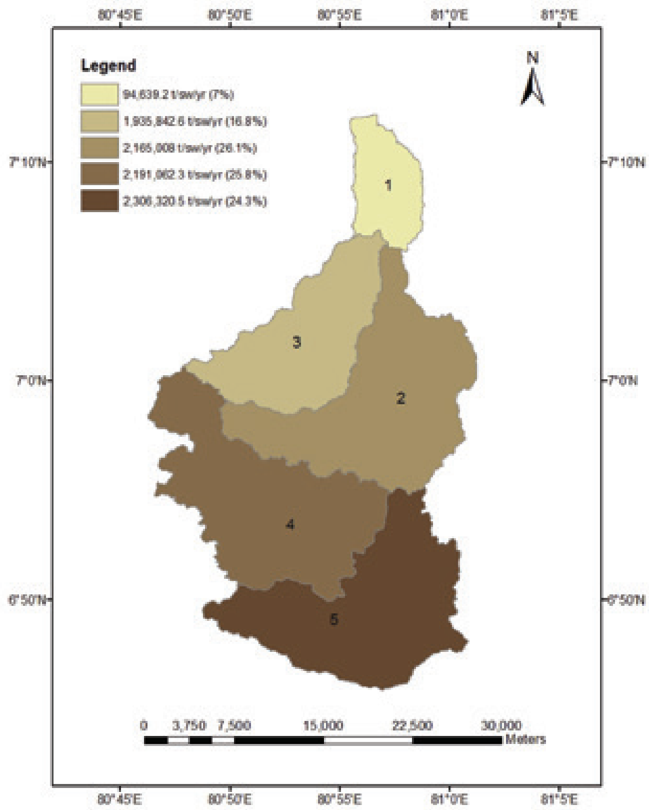



**Figure 11: Pixel based soil erosion (Scenario I)**

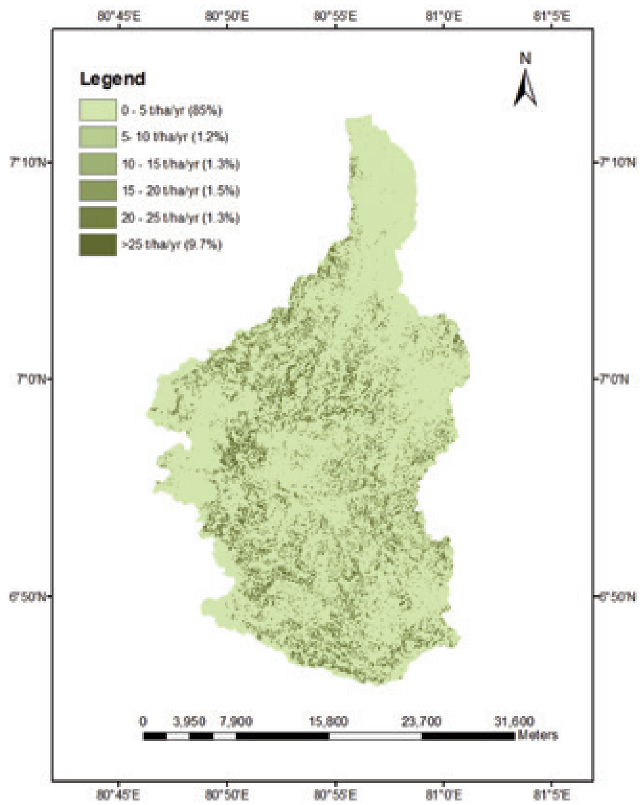


**Figure 12: Pixel based soil erosion (Scenario II)**

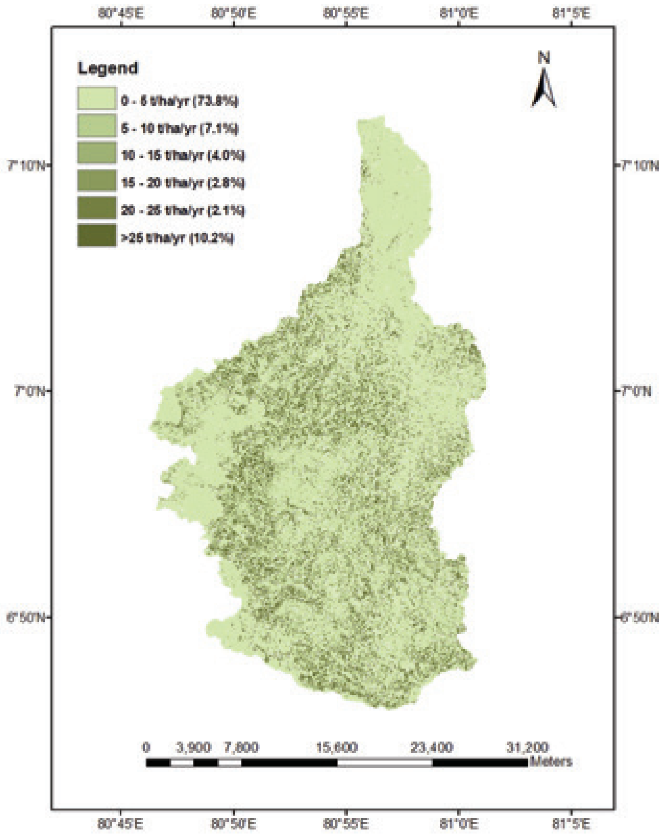



**Figure 13: Pixel based soil erosion (Scenario III)**

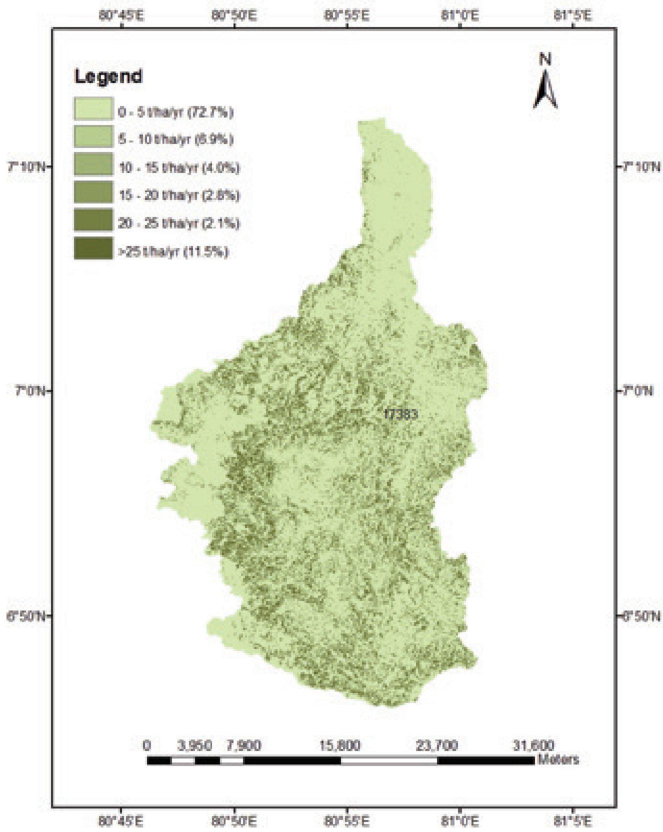
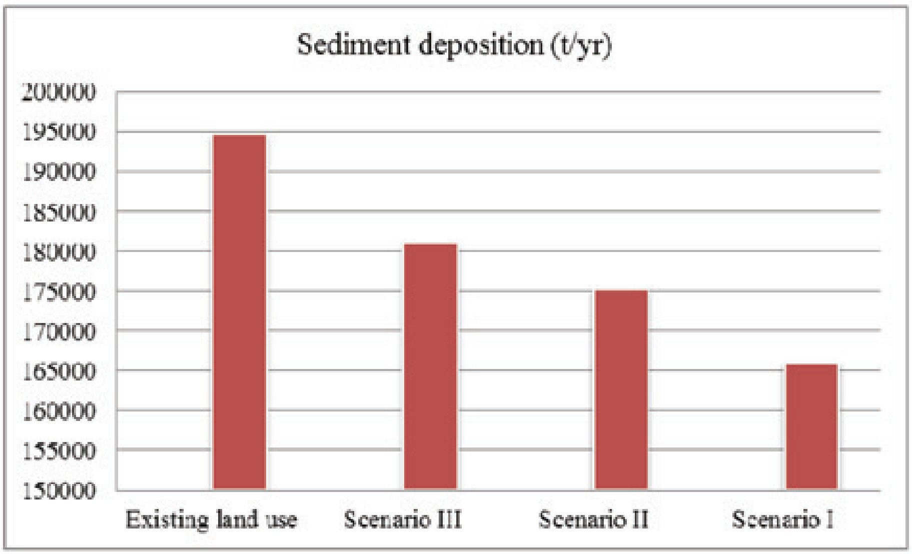


**Figure 14: Sediment depositions (t/yr) at three different scenarios**



**SANDEE**

P.O. Box 8975, E.P.C 1056, Lalitpur, Nepal

Street address: c/o ICIMOD, Khumaltar, Lalitpur, Nepal

**Tel:** 977 1 5003222, **Fax:** 977 1 5003299, **Email:** info@sandeeonline.org, **Web:** www.sandeeonline.org

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